GEOPHYSICS

A New Class of Earthquake Observations

Advances in satellite technology have improved measurements of Earth's properties. Now changes in local gravity resulting from large earthquakes can be detected.

Fred F. Pollitz

A leap in observational geodesy—the science of measuring the size and shape of Earth—occurred 20 years ago with the establishment of several satellite-based measurement systems, including satellite laser ranging (SLR), very long baseline interferometry (VLBI), and the Global Positioning System (GPS). Geodesists exploited these systems to measure crustal deformation and tectonic motion to an accuracy of about 1 cm or better (*1*). Another leap came in the early 1990s with the development of synthetic aperture radar combined with interferometric processing (InSAR) (*2*), which provided centimeter-level accuracy and high spatial resolution. The combined accuracies of GPS for horizontal motions and InSAR for vertical motions have been generally sufficient to capture earthquakes of magnitude $M \geq 5$, allowing the quantification of earthquake ruptures at a level of detail not possible before the mid-1980s.

Geodesists have long anticipated a similar leap in remote sensing of earthquakes by means of gravity signals. This advance was realized with the March 2002 launch of the Gravity Recovery and Climate Experiment (GRACE) twin satellites. This mission is a partnership between NASA and DLR (Deutsche Forschungsanstalt für Luft- und Raumfahrt) and is designed to measure every 30 days the time-variable gravity caused by movement of water mass (*3*). It is based on ranging measurements between two identical satellites that fly in the same low Earth orbit, separated by about 200 km. Because their orbital height is only 500 km, GRACE measures global gravity at unprecedentedly small scales (*4*). Applications of this powerful system include the detection of monthly-variable snow and ice levels on the polar caps, surface water flux on continents, and seafloor pressure fluctuations (*5*, *6*). Soon after it was launched, this new system was also deemed capable of detecting gravity changes associated with $M \approx 9.0$ earthquakes (*7*). On page 658 of this issue, Han and colleagues (*8*) demonstrate an unequivocal observation of the gravity change from an earthquake with satellite-based measurements.

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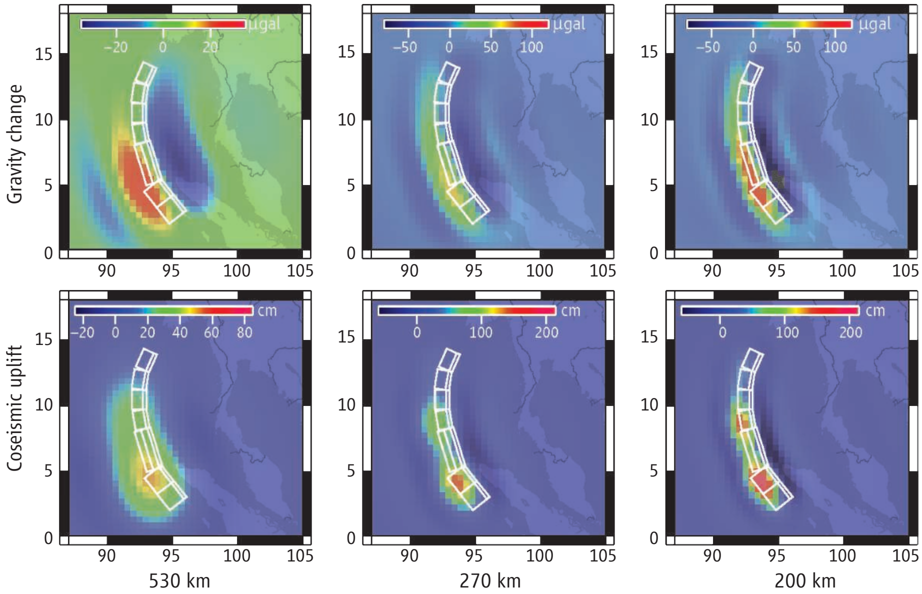

Mapping gravity. Gravity change and uplift at Earth's surface (*18*) computed on the spherical Preliminary Reference Earth Model (*19*) (including an ocean layer) using a refinement of the Banerjee *et al.* (*9*) coseismic slip model of the Sumatra-Andaman earthquake (fault planes are indicated by white outlines). The gravity and uplift fields are filtered at progressively smaller half-wavelengths: 530 km (**left**), 270 km (**middle**), and 200 km (**right**). The left image is comparable to the GRACE gravity observations and model presented by Han *et al.* (*8*).

The earthquake investigated by Han *et al.* is the magnitude 9.2 Sumatra-Andaman earthquake that occurred on 26 December 2004. Having ruptured about 1500 km of the megathrust zone (the long and wide boundary between tectonic plates) of the Sumatran trench, this earthquake is the longest ever recorded. The authors take advantage of the technical capabilities of the GRACE satellites (in particular their onboard GPS receivers and accelerometers) to correct satellite-to-satellite distance measurements for the effects of nongravitational acceleration. By further differencing the gravity fields estimated before and after the earthquake, they isolate the effects of the Sumatra-Andaman earthquake on Earth's gravity field, which range from –15 to +15 microgals, well above the uncertainty in the measurement. (For comparison, gravitational acceleration at Earth's surface is 980 gals.) The processes contributing to this gravity change are (i) the vertical motions of the solid Earth, which rearranges the internal stratification in intrinsic density—for example, bringing relatively high-density rock to a level previously occupied by low-density rock—and (ii) a change in the intrinsic density of the surrounding material, which is induced by permanent dilatation or contraction of the material by the earthquake. At relatively short wavelengths of the static deformation field, the first effect dominates because of the large effect of vertical offset of the seafloor caused by the earthquake (see the figure). However, at longer wavelengths the second effect gains in importance because it is compounded over a volume of large dimensions. At wavelengths greater than 800 km, where the expected signal is well above the measurement error, Han *et al.* find that both effects contribute about equally to the net measured gravity change.

Global static deformation from the Sumatra-Andaman earthquake has been accurately measured by GPS (*9*–*12*), and corresponding dislocation models of net slip have been constructed with these sets of displacements. As is the case for most earthquakes, gaps in coverage by GPS instruments lead to uncertainties in the details of rupture (e.g., depth extent of slip, horizontal variations in slip, etc.). Vertical offsets of the seafloor near the Sumatran trench but away from Sumatra

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and smaller land areas (where GPS instruments are placed) would likely go undetected by GPS instruments but could, in principle, be seen by GRACE measurements. Although not yet investigated, the Aceh basin off the coast of northern Sumatra could provide such a target in order to test the intriguing hypothesis that 15 to 20 m of slip on a secondary thrust structure (*13*) occurred simultaneously with known slip on the megathrust. This secondary thrust is suspected of having contributed to the tsunami that devastated northern Sumatra (*13*).

The successful detection of gravity changes caused by the Sumatra-Andaman earthquake opens the door to the detection of related geophysical phenomena. Gravity fields mapped by GRACE can reveal details at a resolution of about 400 km, but the relatively large observational errors at finer resolution demand large sources with sufficiently large spatial dimensions. Future observations might include detection of postglacial readjustment of Earth's ductile mantle (*14*) at continent-wide scales, strain accumulation at megathrust zones (*15*), and postseismic relaxation of the mantle after a Sumatra-sized earthquake, as has already been detected by GPS (*16*). These processes affect volumes of material extending to several hundreds of kilometers in depth, and high-resolution global gravity measurements should provide good and unique constraints on the depth-dependent nature of the associated mantle flow fields. The detection threshold of these processes will be dramatically improved if the follow-on to GRACE provides data with errors smaller by one to two orders of magnitude (*17*), which would lower the detection threshold of earthquakes to $M \approx 7.5$ (*7*).

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CLIMATE

Caving In to New Chronologies

Speleothems formed in caves, such as stalagmites, can be dated precisely and are increasingly providing detailed and accurate records of past climates.

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When you check the weather forecast on TV, you do not expect it to be completely accurate. But you do expect a degree of certainty about when the forecast is for: It would not be very useful to hear that it will probably be rainy, but with a thousand-year uncertainty about when. Yet this is the situation faced by those studying past climate. Records of climate from sediment or ice cores are not time series but depth series, and converting depth to age generally carries a substantial uncertainty.

Stalagmite tales. Stalagmites such as those shown here can provide highly accurate climate records for the past 400,000 years.

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This is unfortunate because the timing of climatic changes can provide fundamental information about the mechanisms driving that change. A climate change in one region, for instance, could not have been caused by change at a later time in another region. This situation presents paleoclimatologists with a dilemma. Often, the best way to constrain the chronology of a poorly dated record is to line up events in that record with those in a better dated record. But to do so discards information about the phasing of change and therefore about the links between climate in different regions, or between climate and the forces that drive it.

The question of paleoclimate chronology has been given fresh focus by the burgeoning field of climate reconstruction from speleothems—the general term for carbonates found in caves, such as stalagmites (see the first figure). Speleothem climate records can be dated by measuring the growth of thorium-230 from the radioactive decay of uranium, yielding climate chronologies for the past 400,000 years at unprecedented precision. When and how can other climate records be correlated to these well-dated speleothem records?

Some of the best stalagmite records come from regions influenced by the Asian monsoon (*1*, *2*). These records show abrupt changes in monsoon strength on millennial time scales, with a pattern similar to those seen in records from ice and sediment cores from the North Atlantic region. Extreme cold events in the North Atlantic are caused by increases in the flux of fresh water (sometimes from icebergs that carry and deposit coarse-grained sediments as evidence of their past presence). This freshwater flux decreases the rate of deep-water formation and hence the northward transport of heat, leading to cold

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